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Recent interest in physics of Li-like ions for $Z = 20–30$*

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Abstract : The research program on lifetime measurements of metastable states in He- and Li-like ions in the region Z = 20–30 has been progressing well at our center. The beam-foil spectroscopy with single as well as two-foil involving an X-ray solid state detector has resolved intricate problem of satellite line, and in turn, it has provided us reliable lifetime of both the upper levels of He- and Li-like M2 lines. In order to resolve the satellite from He-like M2 line spectrally, we are developing Doppler Tuned Spectrometer (DTS) here. So far, our work has been centered around the 15UD Pelletron accelerator. High current ECR ion source-based injection to the forthcoming LINAC will be more appropriate for above mentioned works. Present activities and future plans of high resolution experiments will be highlighted along with the salient results obtained.

Keywords : Highly charged ions, satellite lines, high resolution X-ray spectroscopy, beam-two-foil spectroscopy.

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1. Introduction

Highly charged atomic systems involve new theoretical regimes, where interactions that are negligible in neutral atoms can become dominant. Because they scale with different power of the nuclear charge Z, relativistic and quantum electrodynamic interaction turn very large. Traditionally 'forbidden' decay processes such as M1, E2, M2, and two-photon (2E1) can exceed 'allowed' E1 processes because of their stronger Z scaling. Rather than being exotic, these highly charged systems dominate high temperature environments such as the solar corona and stellar and laboratory plasmas, and thus all matter in the niverse is in the ionized states. In such systems, the electron binding energy is very large, and the strong Coulomb field has a long range intensity that enhances interaction cross sections. Further, the reduced electron ning causes inner shell effects to become more nt. All of these properties are dependent on Z, which can be treated as a controllable experimental er if reliable data base be available along an electronic sequence.

To prescribe these systems, methods of calculation must undergo conceptual refinements subject to xperimental verifications. At present, the spectral olution of wavelength measured in laboratory and astrophysical plasma is comparable with the accuracy of theoretical calculations and lies in the range of $\Delta\lambda/\lambda$ = 10^{-4} to 10^{-5} for 1–10 Å. However, the accurate specification of wavelength and energy level data does not ensure correct predictions on transition probabilities and lifetimes. Measurements of the lifetimes are particularly important, since they provide absolute rate values necessary to normalize relative transition probabilities obtained by time-integrated techniques. However, most usable method for lifetime measurements, beam-foil spectroscopy (in-flight excitation of a fast ion beam by a thin film), has two intrinsic problems such as cascading and blending due to lines from nearby charge states; in addition, it is a weak source. Cascading problem can be taken care at present to great extent. But blending problem is not addressed clearly in particular, to solve satellite [1] based blending for H- to Li-like ions in region Z =17–45. One can have some idea on satellite blending problem from a level scheme of He- and Li-like Ti as shown in Figure 1. In view of this problem, there are many published results are doubtful [2–4].

Recently, we have shown that our experimental approach combining single-foil and double-foil measurements and applying iterative multi-component exponential growth and decay analysis has resolved

*Invited Talk

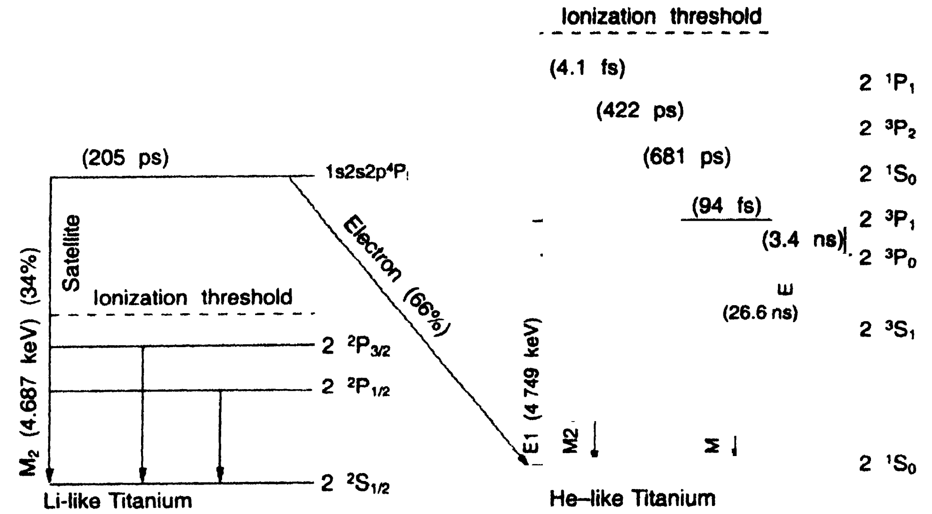

Figure 1. Level scheme of Li- and He-like titanium. Theoretical lifetimes and branching ratios [9–11] are also given, for some levels.

contributions from transitions in other charge states that cannot be spectrally resolved [5,6]. As such, these results establish a benchmark for this method, and could serve to substantiate further results using same technique on yet-unstudied systems, or on systems for which the published results are doubtful. These results could also serve as a caution to other researchers when determining lifetimes using transitions that may be blended with lines from nearby charge states.

There are certain works which have carefully taken care of the above fact, as for example Dohmann *et al* [7] has obtained reliable lifetimes of both Li-like $1s2s2p\ ^4P_{5/2}$ and He-like $1s2p\ ^3P_2$ titanium. Our results [8] compare very well with their measurements as shown in Table 1 ensuring validity of our method. Further, our results support the theoretical calculations [9,10]. It may also be noted that our measured lifetime for He-like $1s2p\ ^3P_2$ nickel [6] is in very good agreement with the theoretical values [10]. It may be worth noting that the titanium as well as nickel are free from hyperfine fields (HFS). An intricate problem arise when the effect of HFS clubs with satellite line blending. If the satellite level lifetime is smaller than the parent one, the satellite blending may cause reduction of the parent level lifetime. At the same time, HFS also does reduces the level lifetime [11]. Thus, one is not able to differentiate the reason of the lifetime reduction. We have made an attempt to study such effect through vanadium and found the results as shown in Table 1. Our experimental results are, expected to be free from satellite blending problem and give an indication that He-like $1s2p\ ^3P_2$ vanadium lifetime is closed to the estimated value (without considering HFS) [10]. In contrast, Li-like $1s2s2p\ ^4P_{5/2}$ vanadium lifetime is much smaller than theoretical estimate (without considering HFS) [9]. This fact implies very well that effect of HFS influences more on Li-like $1s2s2p\ ^4P_{5/2}$ than He-like $1s2p$ $^3P_2$ levels of vanadium. One very good example of the effect of HFS on Li-like chlorine $1s2s2p\ ^4P_{5/2}$ level lifetime can be noticed in Sellin *et al* [12]. They found that the measured lifetime (0.91 ± 0.04 ns) was much smaller than the theoretical estimate (1.98 ns) [13]. Later Cocke, *et al* [14] verified the measurement to get similar value (0.95 ± 0.2 ns). Our recent observation in vanadium suggests [5] that the difference in theory and measurement in chlorine may be due to the same reason of HFS However, there is no theoretical result yet on the effect of HFS on Li-like $1s2s2p\ ^4P_{5/2}$ level lifetimes.

Table 1. Lifetimes obtained in our laboratory with novel beam-single-foil and beam-two-foil experiments for He- like $1s2p\ ^3P_2$ and Li-like $1s2s2p\ ^4P_{5/2}$ state of Ti, V and Ni and compared with reliable experiments and theoretical estimates.

Ion	Upper level	Line energy (keV)	Experiment (Our work)	Experiment (Other works)	Theory
Ti^{19+}	$1s2s\ ^4P_{5/2}$	4.78	404 ±16 [7]	404 ± 40 [11]	422 [10]
Ti^{20+}	$1s2p\ ^3P_2$	4.78	210 ±10 [7]	236 ± 12 [8]	212 [9]
Ni^{26+}	$1s2p\ ^3P_2$	7.8	70 ± 3 [6]	-	70.6 [10]
V^{20+}	$1s2s2p\ ^4P_{5/2}$	5.17	123 ± 13 [5]	-	159 [9]
V^{21+}	$1s2p\ ^3P_2$	5.17	314 ± 21 [5]	-	310 [10]

2. Experiment

The experiments are being carrying out with Ti, V and Ni beam from the Pelletron at our center in the energy range of 90–165 MeV. The experimental details for V and Ni experiments can be seen from earlier papers [5,15] and recently, the setup has been entirely changed to cover larger flight path. Using these two setups, we have obtained lifetimes for He-like $1s2p\ ^3P_2$ state and Li-like $1s2s2p\ ^4P_{5/2}$ state as shown in Table 1 and compared to earlier reliable experiments. Further, we have found the relative charge state fraction of Li-like to He-like ions from the multicomponent iterative analysis from single foil as well as two-foil data [5,16]. Relative charge state fractions obtained from single as well as two-foil data in this procedure, agree very well with each other.

Present setup is having an option of changing the second foil to vary thickness and to give an opportunity to measurements on post collisional beam such as charge state analysis or doing γ-spectroscopy of the residual nuclei, *etc*. A schematic and a photograph in Figure 2. shows X-ray spectroscopy and γ-spectroscopy. We have a plan to use electrostatic analyzer in future also to have concrete idea on post collisional charge states so that the data obtained in Table 2 can also be compared with measured charged state fraction data. An inclined straight electrostatic charge state analyzer has already been fabricated as shown in Figure 3.

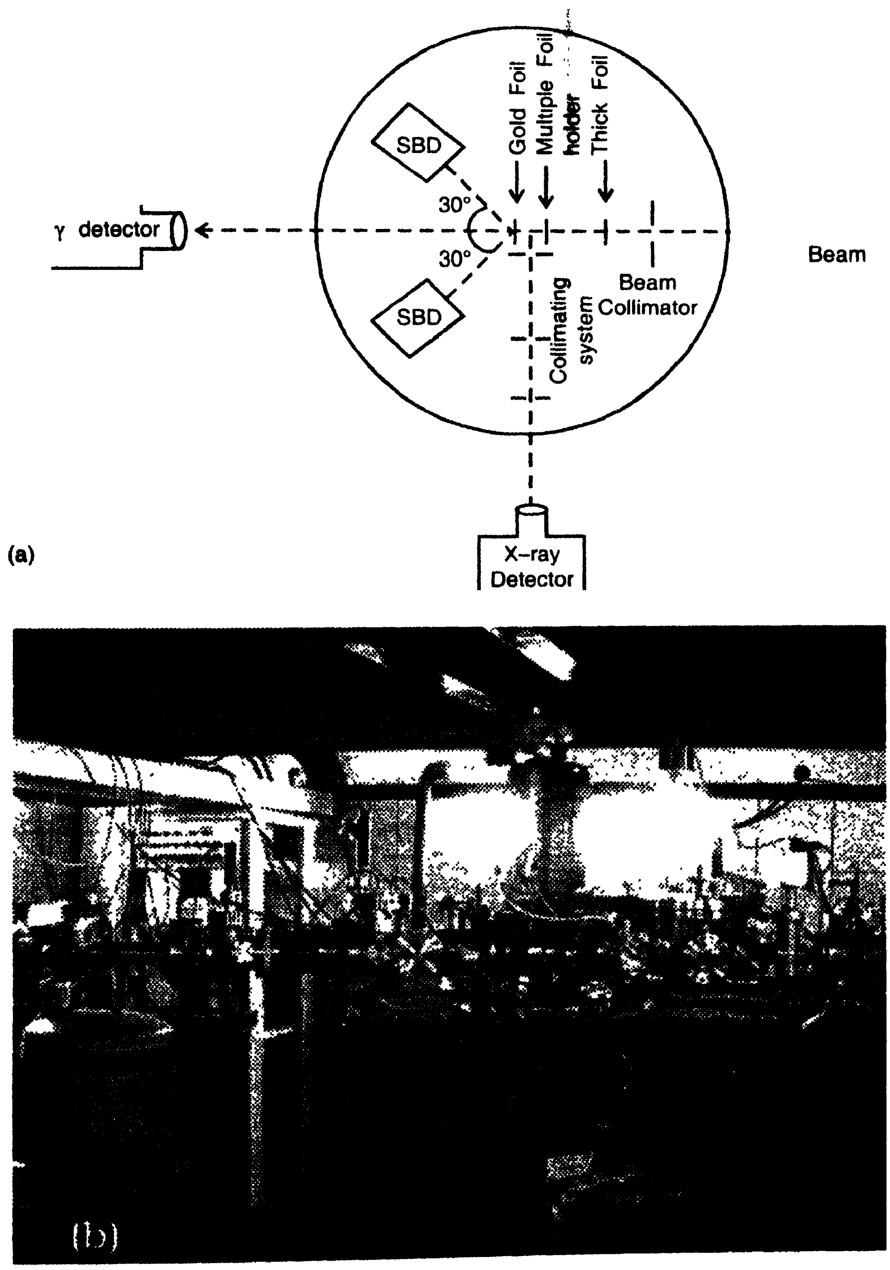

Figure 2. (a) Schematic of the present beam–single-foil and beam–two-foil experiments at NSC and (b) Photograph of the same set up.

Table 2. The relative level population of $1s2p2s$ $^4P^o_{5/2}$ to $1s2p$ $^3P^o_2$ is compared at different beam energies in the single-foil as well as the two-foil experiment.

Beam energy (MeV)	Intensity ratio single foil experiment	Intensity ratio two-foil experiment
100	11.67 [2], 12.7 [3]	11.67 [2], 11.28 [3]
158	5.89 [2], 6.4 [3]	6.45 [2], 5.97[3]

3. Discussion

Present method needs some assumptions in the analysis of experimental data, as the transitions from satellite transitions are not resolved experimentally. We have planned high resolution experimental methods; *viz.* Doppler tuned spectroscopy [17]; to confirm the present results directly in several ions in the Z = 20–30 range. A schematic diagram of our Doppler tuned spectrometer is shown in Figure 4.

Apart from reliable lifetime measurements of He-like $1s2p$ $^3P_2$ state and Li-like $1s2s2p$ $^4P_{5/2}$ state in the range of Z = 20–30, we have confirmed the intrashell transition [18] between $2s$–$2p$ and *vice versa* during the

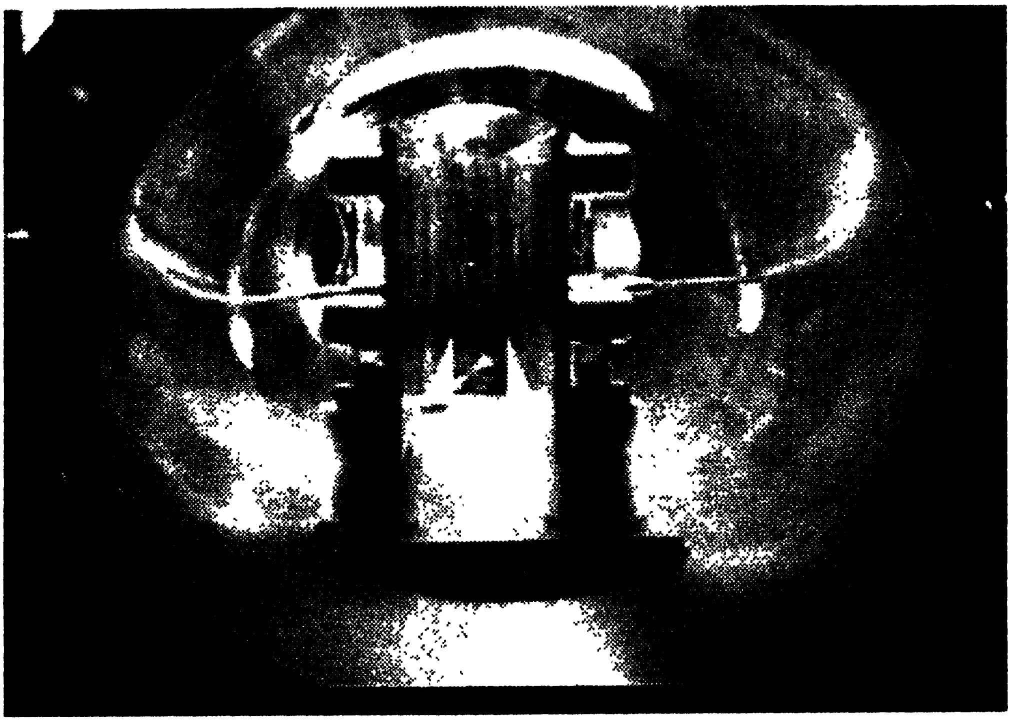

Figure 3. Inclined straight electrostatic analyzer fabricated at NSC.

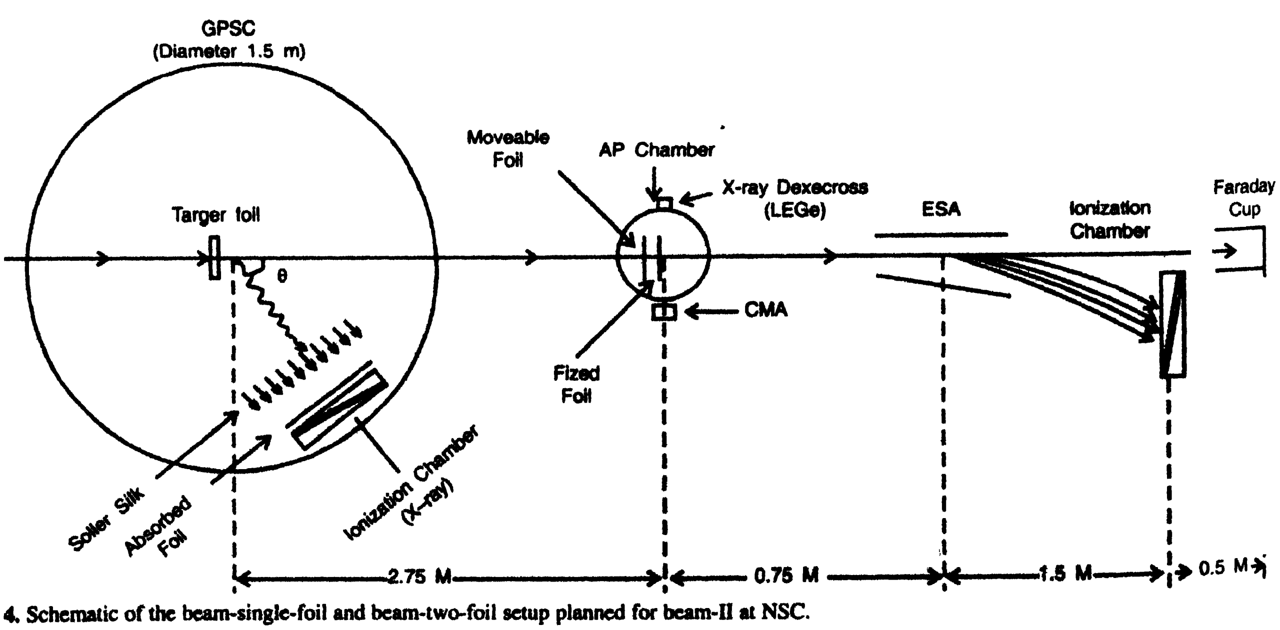

Figure 4. Schematic of the beam-single-foil and beam-two-foil setup planned for beam-II at NSC.

collisions with thin carbon foil for the first time [19]. Further, three body recombination processes known as ternary recombination [20] has also been observed for the first time with the bared Zn ions [21]. Statistical accuracy of the data from beam-foil experiments can only be improved with high beam current. This sort of novel facility is going to be available in a couple of years at out center with superconducting electron cyclotron resonant ion source-based linear accelerator [22]. Besides high current, higher energy will also be available to enable us to enhance statistical accuracy with enhanced charge state fraction for He-and Li-like ions.

4. Conclusion

In summary, experiments [5–8,12,14] which take care of satellite blending issue provide very good agreements with the theories [9,10] for HFS-free atomic systems. However, situation reverts for HFS-affected atomic systems. Lifetime of Li-like chlorine $1s2s2p\ ^4P_{5/2}$ state [12–14] may be quenched as large as 50% by effects of HFS. Effect on Li-like vanadium was found some what smaller ~21% [5]. Interestingly HFS does not affect He- like vanadium $1s2p\ ^3P_2$ state equally [5]. Such unusual observations indicate that studies on Li-like ions in Z = 20–30 may be very interesting. Theoretical investigation in support of our observation are welcome.

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References

[1] A H Gabriel and C Jordan *Nature* **211** 947 (1969)

[2] H Gould, R Marrus and P J Mohr *Phys. Rev. Lett.* **33** 676 (1974)

[3] A Simionovici, B B Birkett, J P Briand, P Charles, D D Dietrich, K Finlayson, P Indelicato, D Liesen and R Marrus *Phys. Rev.* **A48** 1695 (1993)

[4] S Cheng, H G Berry, R W Dunford, D S Gemmel, E P Kanter, C Kurtz, K E Rehm and B J Zabransky *Phys. Rev.* **A50** 2197 (1994)

[5] T Nandi, P Marketos, P Joshi, R P Singh, C P Safvan, P Verma, A Mandal, A Roy and R K Bhowmik *Phys. Rev.* **A66** 052510 (2002)

[6] T Nandi, Aijaz A Wani, Nissar Ahmad, R P Singh, R Ram and S Ahmad *J. Phys.* **B37** 703 (2004)

[7] H D Dohmann, R Mann and E Pfeng *Zeits. Phys.* **A309** 101 (1982)

[8] T Nandi, Nissar Ahmad, Aijaz A Wani and P Marketos *J. Phys.* **B** (Submitted) (2004)

[9] M H Chen, B Crasemann and H Mark *Phys. Rev.* **A24** 1852 (1981); K Cheng, C Lin and W R Johnson *Phys.Lett.* **A48** 437 (1974); U I Safronova, V S Senashenko and I A Shavtvalishvili *Physika (in Russian)* **12** 13(1977)

[10] I P Grant, C F Fischer and F A Parpia *GRASP-1992* (private communication)

[11] W R Johnson, K T Cheng and D R Plante *Phys. Rev.* **A55** 2728 (1997)

[12] I A Sellin, D J Pegg, P M Griffin and W W Smith *Phys. Rev. Lett.* **28** 1229 (1972)

[13] G W F Drake *Phys. Rev.* **A3** 908 (1971)

[14] C L Cocke, B Curnutc and J R Macdonald *Nucl. Instrum. Meth.* **110** 493 (1973)

[15] T Nandi *Indian J. Phys.* **76B** 407 (2002)

[16] T Nandi *NSC Annual Report* 2002-03 p239

[17] C L Cocke, B Curnutte, J R Macdonald and R Randall *Phys. Rev.* **A9** 57 (1974)

[18] J H McGuire, D J Land, J G Brennan and G Basbas *Phys. Rev.* **A19** 2180 (1979)

[19] T Nandi, Nissar Ahmad and Ranjeet Karn *NSC Annual Report (2003-04)* p179

[20] D'Angelo *Phys. Rev.* **121** 505 (1961)

[21] T Nandi, Nissar Ahmad and Ranjeet Karn *NSC Annual Report (2003-04)* p180

[22] D Kanjilal *et al NSC Annual Report (2002-03)* p31